

A Case Study of Modal Mass Acceleration Curve Loads vs. Sine Loads

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Outline

- Introduction
 - MMAC Background
 - Case Study
 - *Mission*
 - *MMAC Analysis*
 - *Sine Analysis*
 - Comparison
 - Conclusion
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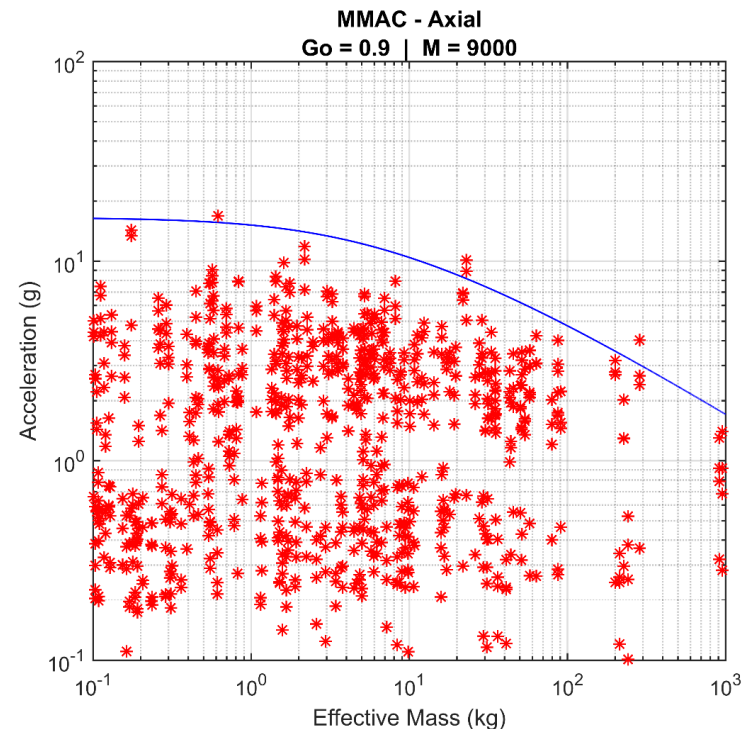
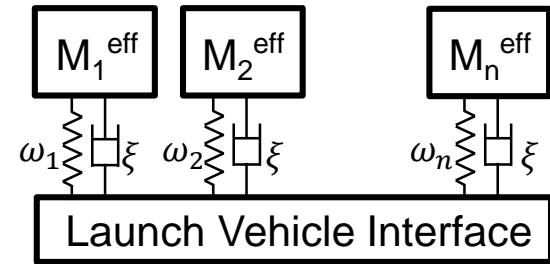
Introduction

- Per JPL 30 years of experience, Modal Mass Acceleration Curve (MMAC) approach bounds Coupled Loads Analyses (CLA) results while not being overly conservative. However, most spacecraft industries use sine loading.
 - *JPL Past Projects supported by MMAC:*
 - Galileo (1989), SIR-C (1994), Cassini (1997), Deep Space 1 (1998), SRTM (2000), MER (2003), MSL (2011), SMAP (2015)
 - *JPL On-going Projects supported by MMAC:*
 - M2020 (2020), Europa (2020s), NISAR (2020)
- The purpose of this study is to compare the MMAC and sine analyses results, against CLA results.
 - Per this study, sine analysis results have shown deficiencies in comparison to CLA however, MMAC analysis results have been bounding

Background

MMAC Analysis

- Successfully implemented at JPL over the past 30 years for spacecraft launch loads for all JPL missions.
- Innovative extension of the PMAC loads analysis method to modal models of spacecraft structure.
- MMAC is based on the principle that the acceleration response of a base driven system is inversely proportional to the square root of mass.
- Each mode is treated as a single DOF system fixed at Spacecraft to LV interface with some effective mass
- MMA-Curve bounds the magnitude of the modal accelerations as a function of effective mass of each mode



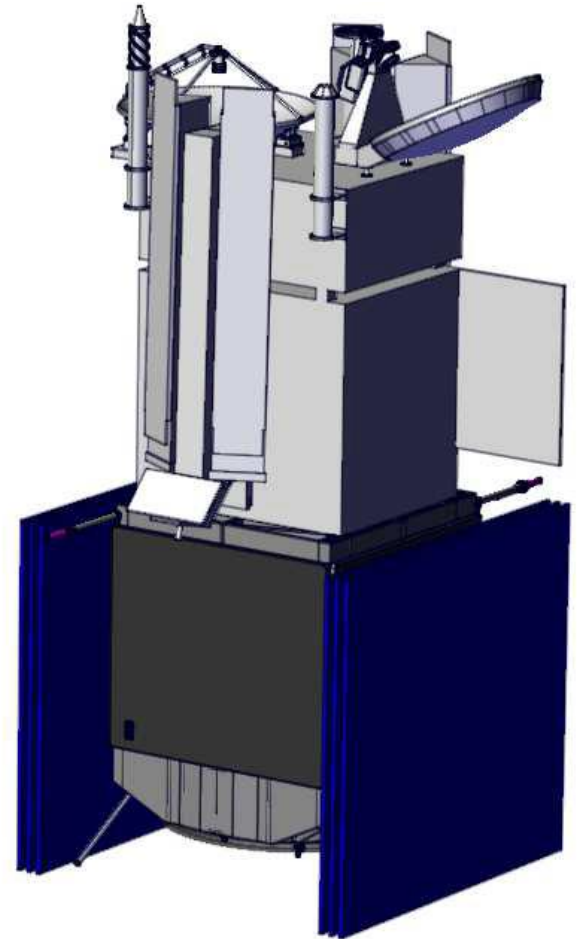
Background

MMAC Analysis

- MMAC Advantages
 - *Quick turnaround:*
 - Load analysis for a payload are done in few days
 - *Large output request:*
 - Possible to output loads for the entire payload model
 - *Launch Vehicle Models*
 - Launch vehicle models and forcing functions are not required
- Considerations
 - *Bounding Loads:*
 - Provides bounding loads for the low frequency launch dynamic environments (<100 Hz) – not a simulation
 - *Not intended to replace the CLA*
 - Intended to support structural design between CLA cycles

Mission

- Joint project between JPL and an international partner
- Sine analysis are required for estimating the low frequency launch loads
- Mission type: Earth orbiting Satellite
- Mass: ~ 2000 kg
- Launch Vehicle
 - *Space X Falcon 9*
- This study uses Hurty/Craig-Bampton model of the spacecraft (CLA model)



MMAC Analysis

Inputs

- Inputs
 - *FEM of Payload:*
 - To get the constraint modes, inertia relief modes , fixed-base normal modes
 - *Payload to Launch Vehicle Interface Accelerations:*
 - Dynamic and mean components
 - Tuned to bound the CG load factors
 - *Modal Mass Acceleration Curve:*
 - CLA results from the current project or previous projects with similar configurations and launch vehicle

Accelration Bound Estimate

$$|\ddot{x}(t)| = \sum_{r=1}^6 |\phi_r^{cm} \ddot{x}_r^{mean}| + \sqrt{\sum_{r=1}^6 (\phi_r^{cm} \ddot{x}_i^{dyn})^2 + \sum_{s=1}^n (\phi_s^{nm} \sqrt{m_s^{eff}} \ddot{q}_s^{MMAC})^2}$$

\ddot{x}_r^{mean} = P/L to L/V interface accel. (mean)

$\ddot{x}_r^{dyn.}$ = P/L to L/V interface accel. (dynamic)

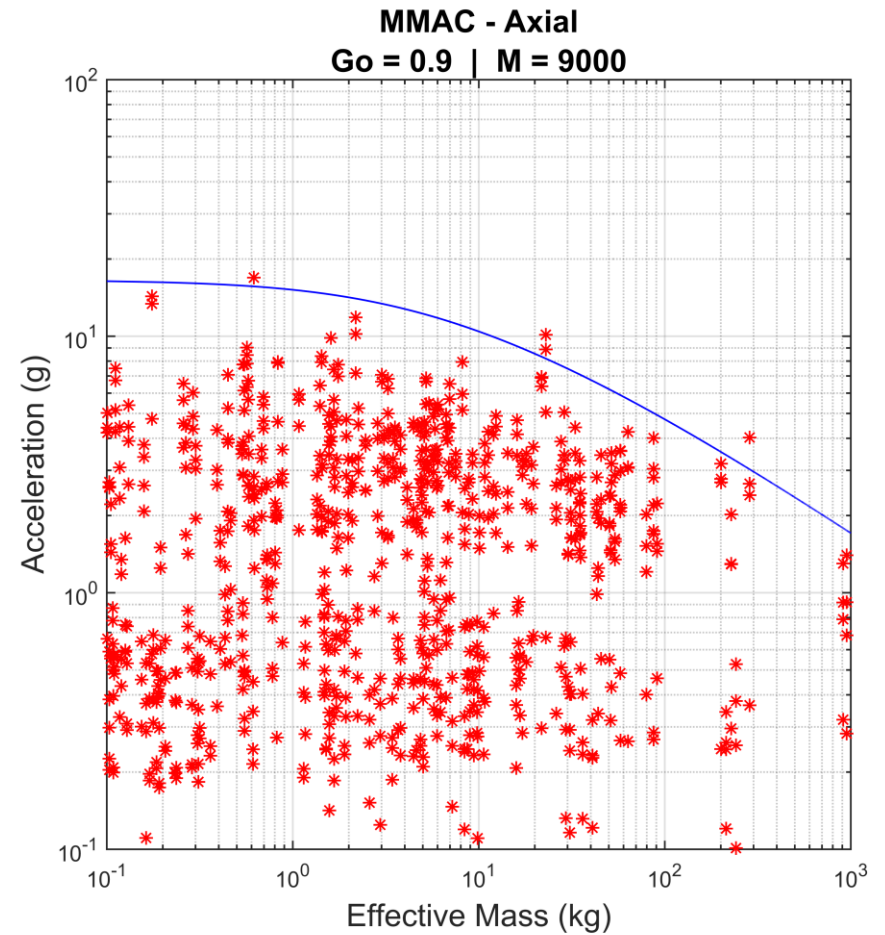
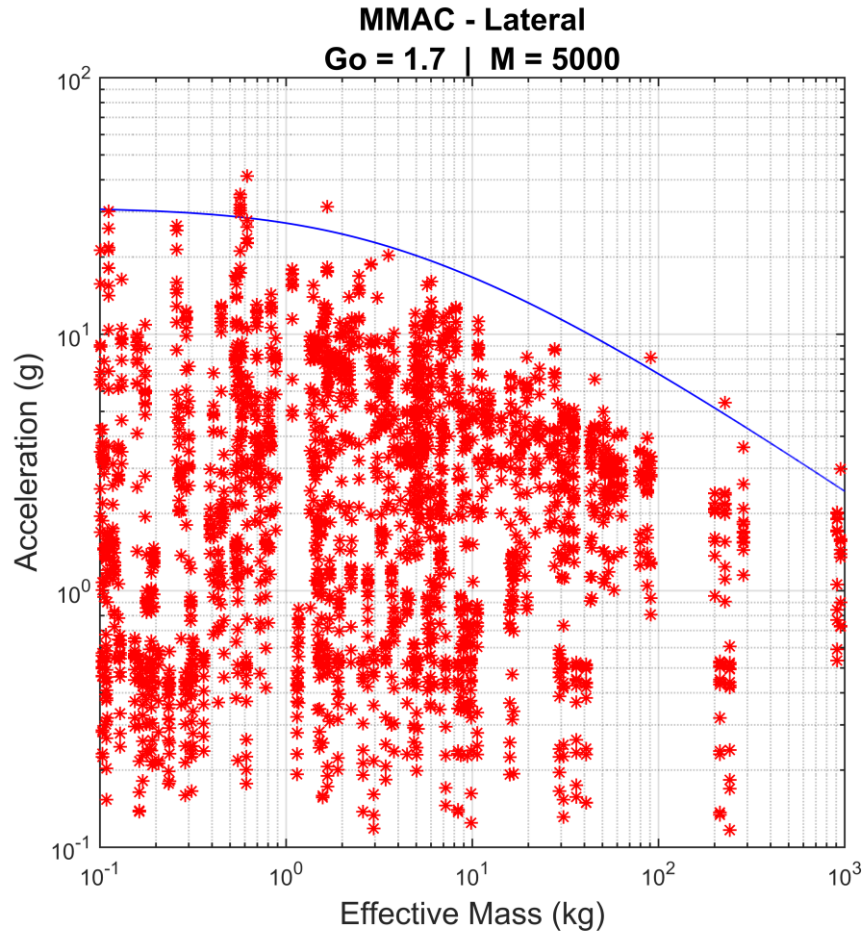
$\sqrt{m_s^{eff}}$ = Effective mass, square-rooted

\ddot{q}_s^{MMAC} = Modal Mass Acceleration



MMAC Analysis

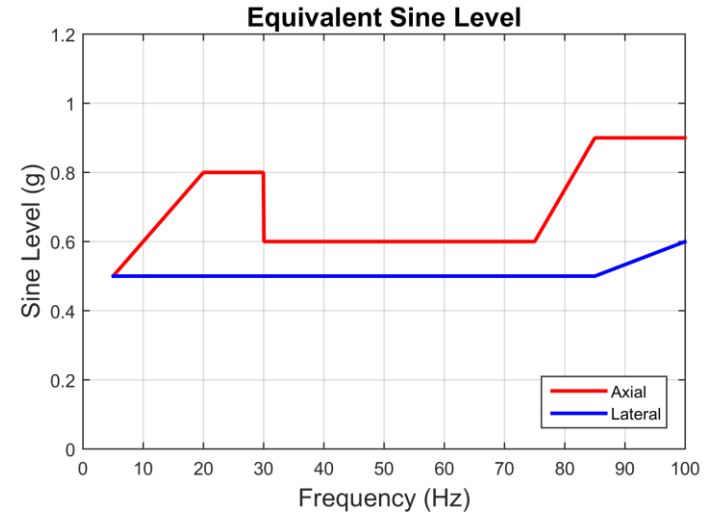
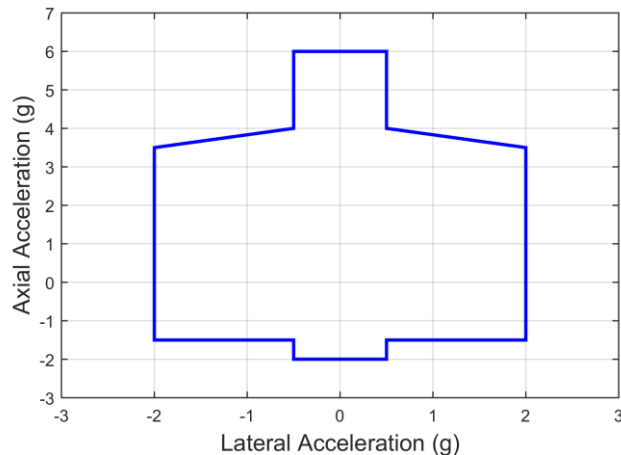
Parameters



Sine Analysis

Summary

- SpaceX Falcon 9 Version 1.1
- 2% Damping
- Sine Environment
 - *Planner's guide*
- Force limiting
 - *CG Load Factors (higher of the CLA and the value given in the planner's guide)*
 - *2.5 g for the lateral case*



Axial

Lateral

Freq. (Hz)	Accl. (g)
5	0.5
20	0.8
30	0.8
30	0.6
75	0.6
85	0.9
100	0.9

Freq. (Hz)	Accl. (g)
5	0.5
85	0.5
100	0.6

CLA Analysis

Summary

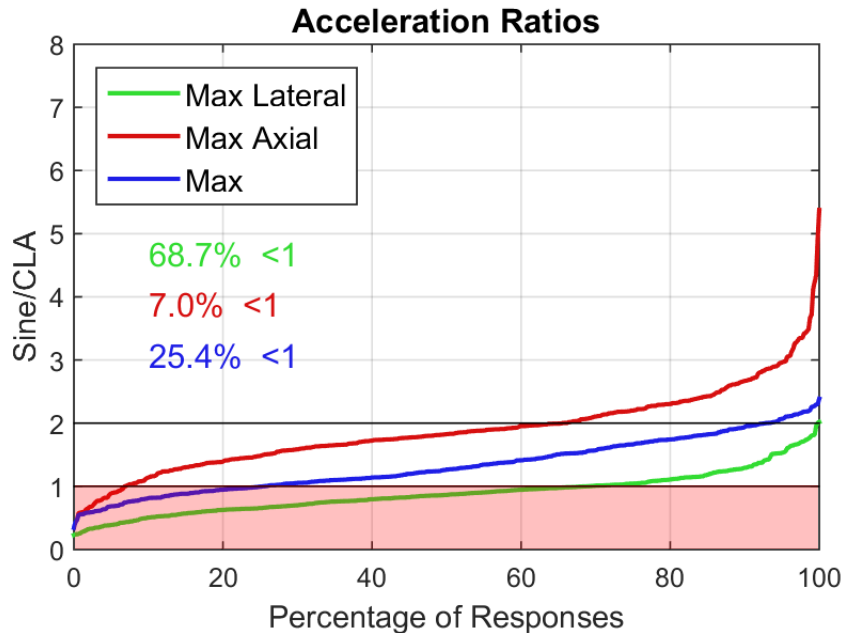
- Early Coupled Loads Analysis
 - *Falcon 9, Version 1.1*
 - *1% Damping*
 - *Frequency Range: $f < 100$ Hz*
 - *Only acceleration results available*
 - *Standard suite of Falcon 9 CLA events*
 - *Dynamic Uncertainty Factor: 1.5*
 - *Static Uncertainty Factor: 1.0*



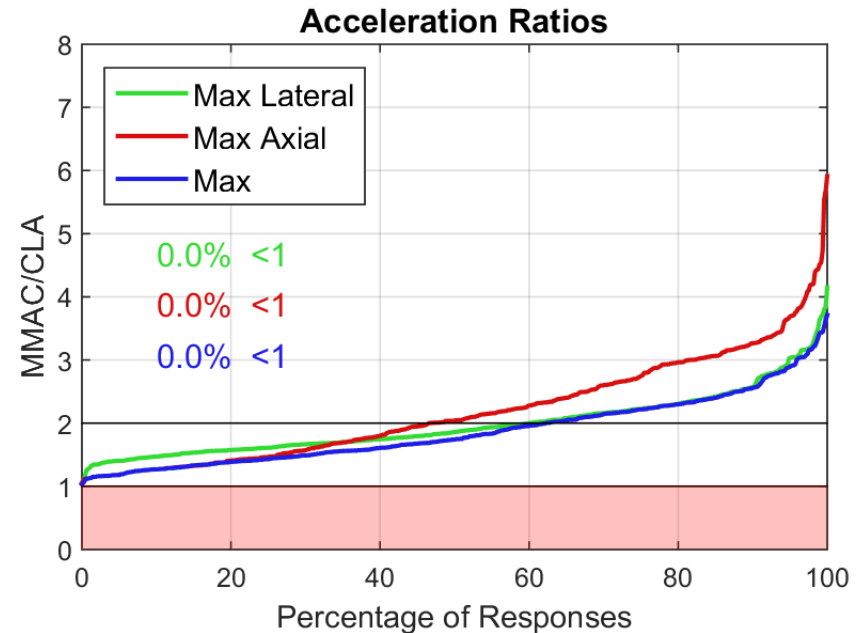
CLA Coverage

Sine vs MMAC

Sine vs CLA



MMAC vs CLA

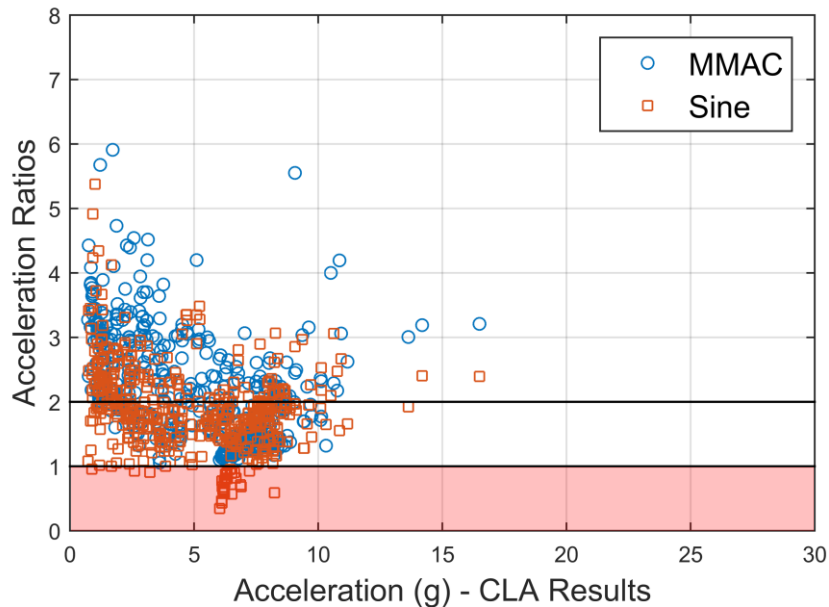


- Sine results are deficient by 68.7% in the lateral case, 7% in the axial case, and 25.4 in the overall maximum case
- MMAC provides full coverage for all three cases without excessive conservatism

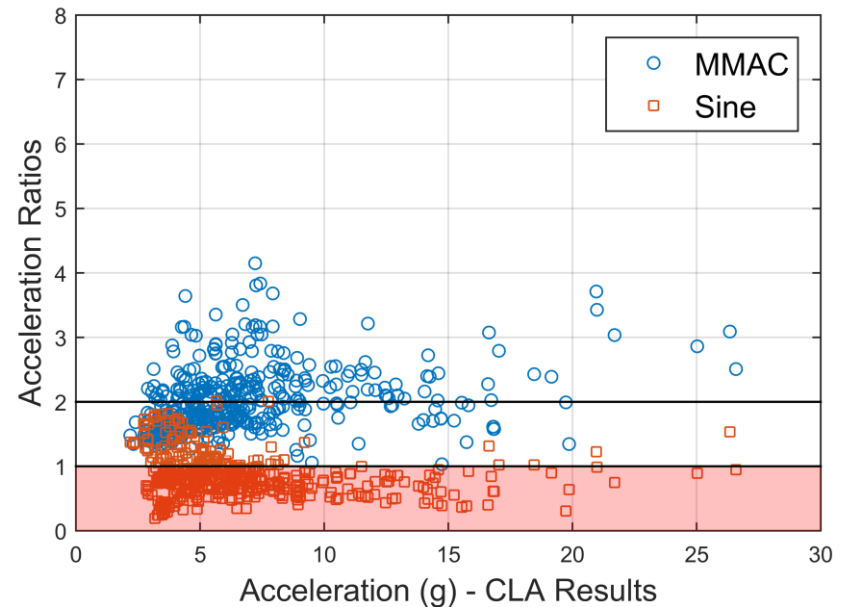
CLA Coverage

Sine vs MMAC

Axial



Lateral



- Deficiencies are observed across the entire range of acceleration values

Conclusions

- Sine analysis showed notable deficiency when compared against the CLA accelerations in this example
 - *Sine environment is not representative of the actual flight environment and may be the source of the deficiencies*
 - Sine waveform is not representative of the actual acceleration time histories at the SC to LV interface
 - Sine is driven in only one DOF; actual flight environment drives all six DOFs simultaneously
 - Sine primarily drives a single mode; actual flight environment drives multiple modes at once
 - Sine capture only the dynamic component of interface acceleration; it does not capture the steady-state acceleration.
 - *For design purposes the higher result from the two analyses (CLA and sine analysis) should be used*
- MMAC provided a full coverage of the CLA results and does not have the shortcoming identified with the sine environment
 - *MMAC analyses is more representative of the flight environment than sine*
- Future Work
 - *Comparison of loads data in addition to the accelerations*
 - *Data comparison from other missions: SMAP, M2020, ...*

Thank you

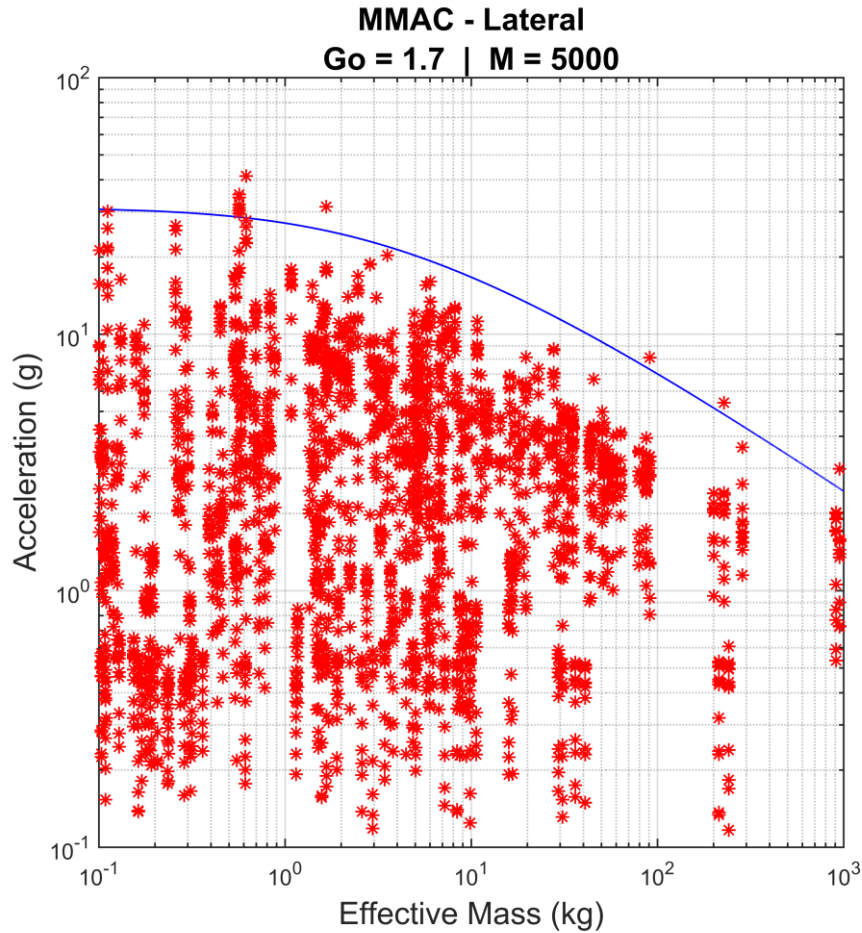


Backup slides



MMAC Analysis

Equation



$$MMAC(m) = \frac{Go}{\sqrt{\frac{m}{M} + (\xi_{sc} + \xi_{lv})^2}} e^{\frac{-\alpha}{\tan(\alpha)}}$$

$$\alpha = \tan^{-1} \left(\frac{\sqrt{\frac{m}{M}}}{\xi_{sc} + \xi_{lv}} \right)$$

MMAC Analysis

Summary

Max Lateral

	Mean	Dynamic
Tx	0.0	1.5
Ty	0.0	1.5
Tz	2.0	0.25
Rx	0.0	0.0
Ry	0.0	0.0
Rz	0.0	0.0

$G_o = 1.7$
 $S_w = 5000 \text{ lbf}$
 $\text{Fact} = 1.0$
 $F_{\max} = 100 \text{ Hz}$
 $\text{Damping} = 1\%$

Max Axial

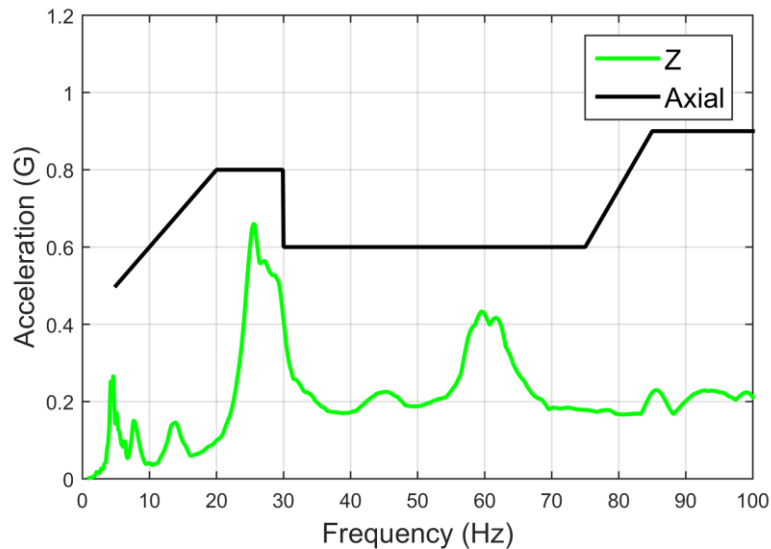
	Mean	Dynamic
Tx	0.0	0.0
Ty	0.0	0.0
Tz	5.0	0.8
Rx	0.0	0.0
Ry	0.0	0.0
Rz	0.0	0.0

$G_o = 0.9$
 $S_w = 9000 \text{ lbf}$
 $\text{Fact} = 1.0$
 $F_{\max} = 100 \text{ Hz}$
 $\text{Damping} = 1\%$

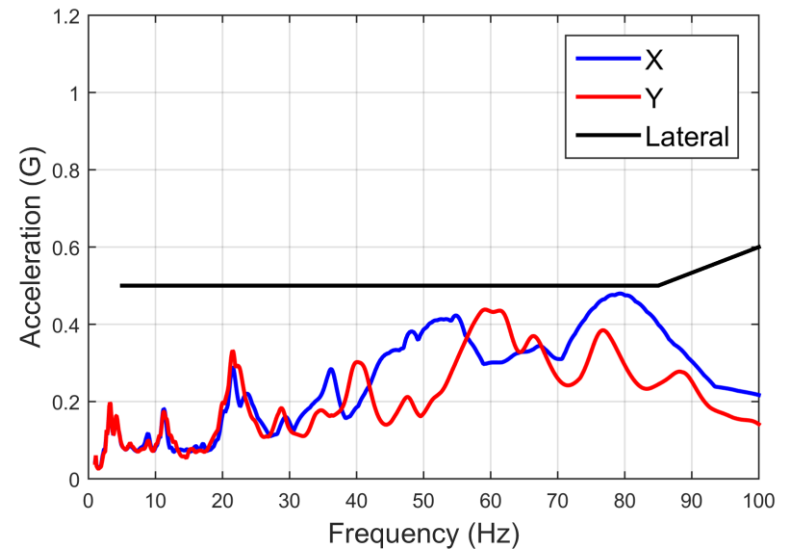
Interface Equivalent Sines from CLA Analysis

Compared with Sine Input Levels

Axial



Lateral

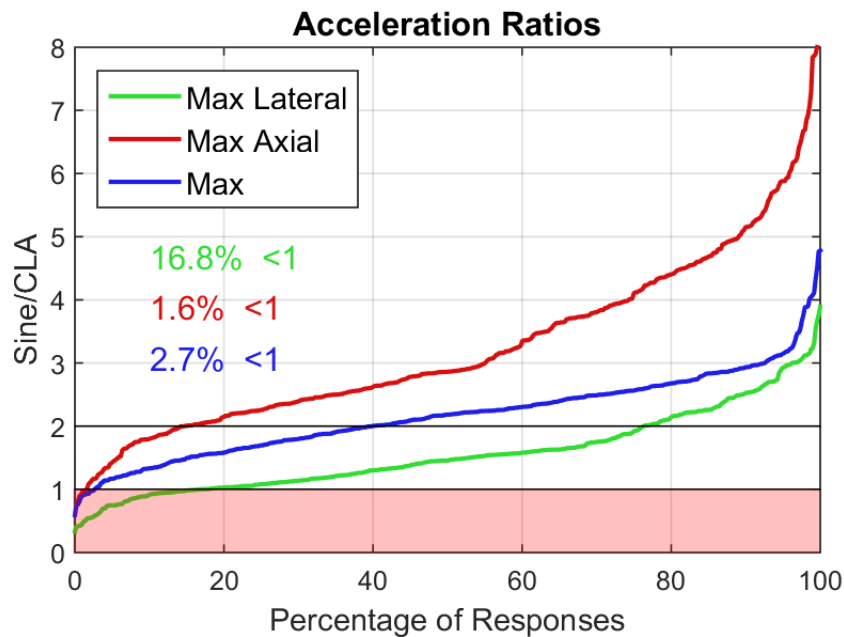


- Sine input levels cover the equivalent sines from CLA analysis

CLA Coverage

Sine vs MMAC

Sine vs CLA



- Using 1% damping significantly improves the coverage but deficiencies are still observed in all three cases
 - *Max Lateral* : 16.8%
 - *Max Axial* : 1.6%
 - *Max* : 2.7%